Falsifying leptogenesis for a TeV scale $W_R^\pm$ at the LHC

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We point out that the discovery of a right-handed charged gauge boson $W_R^\pm$ with mass of around a few TeV, for example through a signal of two leptons and two jets that has been reported by CMS to have a 2.8σ local excess or through a signal of a resonance decaying into a pair of standard model (SM) gauge bosons showing a local excess of 3.4σ (2.5σ global) reported by ATLAS search, will rule out all possibilities of leptogenesis in all classes of the left-right symmetric extensions of the Standard Model (LRSM) with both triplet and doublet Higgs scalars due to the unavoidable fast gauge mediated $B - L$ violating interactions $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$. Our conclusions are very general in the sense that they do not necessarily demand for a lepton number violating detection signal of $W_R^\pm$.

The Left-Right Symmetric Model (LRSM) [1] is one of the most popular candidates for extensions of the Standard Model (SM) of particle physics. In LRSM the Standard Model gauge group is extended at higher energies to

$$\mathcal{G}_{LR} \equiv SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

where $B - L$ is the difference between baryon (B) and lepton (L) numbers. Left-right symmetry breaking predicts the existence of a massive right-handed charged gauge boson ($W_R^\pm$). In this Letter, we point out that if $W_R^\pm$ has a mass of a few TeV and can be detected at the LHC, it will have profound consequences for our understanding of the baryon asymmetry of the Universe. This is a unique situation where by observing $W_R^\pm$ at the LHC, we can make a very strong statement about our origin, that is regarding the baryon asymmetry of the Universe. One of the most attractive mechanisms to generate the baryon asymmetry is leptogenesis, in which a lepton asymmetry is created before the electroweak phase transition, which then gets converted to the baryon asymmetry in the presence of $(B + L)$ violating anomalous processes [2]. Detection of a TeV scale $W_R^\pm$ at the LHC would imply violation of $(B - L)$ at a lower energy, which will rule out all scenarios of leptogenesis. In this context we must mention that an excess of $2.8\ \sigma$ level was observed in the energy bin $1.8\,\mathrm{TeV} < M_{lljj} < 2.1\,\mathrm{TeV}$ in the two leptons two jets channel at the LHC by the CMS experiment [3], which can be interpreted as due to $W_R^\pm$ decay by embedding the conventional LRSM with $g_L \neq g_R$ in $SO(10)$ [4] and with $g_L = g_R$ by taking into account the CP phases and non-degenerate masses of heavy neutrinos

[5]. More recently, the ATLAS search has also reported a resonance that decays to a pair of SM gauge bosons to show a local excess of 3.4σ (2.5σ global) in the WZ final state at approximately $2\,\mathrm{TeV}$ [6], which can naturally be explained by a W_R in the LRSM framework with a coupling $g_R \sim 0.4$ [7].

In the LRSM the fermion sector transforms under the gauge group $\mathcal{G}_{LR}$ as:

$$l_L : (1, 2, 1, -1), \ \ l_R : (1, 1, 2, -1),$$
$$Q_L : (3, 2, 1, \tfrac{1}{3}), \ \ Q_R : (3, 1, 2, \tfrac{1}{3}). \qquad (1)$$

In a popular version of the LRSM, the Higgs sector consists of one bi-doublet Φ and two triplet $\Delta_{L,R}$ complex scalar fields with the transformations

$$\Phi : (1, 2, 2, 0), \ \ \Delta_L : (1, 3, 1, 2), \ \ \Delta_R : (1, 1, 3, 2) \qquad (2)$$

The left-right symmetry is spontaneously broken to reproduce the Standard Model and the smallness of the neutrino masses can be taken care of by the see-saw mechanism [8]. The symmetry breaking pattern follows the scheme

$$\mathcal{G}_{LR} \ \xrightarrow{\langle \Delta_R \rangle} \ SU(3)_C \times SU(2)_L \times U(1)_Y \equiv \mathcal{G}_{SM}$$
$$\xrightarrow{\langle \Phi \rangle} \ SU(3)_C \times U(1)_{EM} \equiv \mathcal{G}_{EM} \qquad (3)$$

In the first stage of symmetry breaking the right-handed triplet Δ_R acquires a Vacuum Expectation Value (VEV) $\langle \Delta_R \rangle = \frac{1}{\sqrt{2}} v_R$ which breaks the $SU(2)_R$ symmetry and gives masses to the $W_R^\pm$, Z_R bosons. The electroweak symmetry is broken by the bi-doublet Higgs Φ, which gives masses to the charged fermions and the gauge bosons $W_L^\pm$ and Z_L. The Δ_L gets an induced seesaw tiny VEV, which can give a Majorana mass to the left-handed neutrinos. The generators of the broken gauge groups are then related to the electric charge by the modified Gell-Mann-Nishijima formula $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$.

In a variant of the LRSM with triplet Higgs scalars, one considers only doublet Higgs scalars to break all the symmetries. This scenario is more popular in all superstring inspired models. Here the Higgs sector consists of doublet scalars

$$\Phi : (1,2,2,0), \quad H_L : (1,2,1,1), \quad H_R : (1,1,2,1), \quad (4)$$

and there is one additional singlet fermion field S_R $(1,1,1,0)$ in addition to the fermions mentioned in Eq. (1). The doublet Higgs scalar H_R acquires a VEV to break the left-right symmetry and results in mixing of S with right-handed neutrinos, giving rise to one light Majorana neutrino, and one heavy pseudo-Dirac neutrino or two Majorana neutrinos.

In the conventional LRSM, the left-right symmetry is broken at a fairly high scale, $M_R > 10^{10}$ GeV. First, the gauge coupling unification requires this scale to be high, and second, thermal leptogenesis in this scenario gives a comparable bound. One often introduces a parity odd scalar and gives a large VEV to this field. This is called D-parity breaking, which may then allow $g_L \neq g_R$ even before the left-right symmetry breaking, and hence, this allows gauge coupling unification with TeV scale M_R. This is true for both triplet and doublet models of LRSM. Embedding the LRSM in an $SO(10)$ GUT framework, the violation of D-parity at a high scale can explain the CMS TeV scale W_R signal for $g_R \approx 0.6 g_L$ [4].

For a TeV scale $W_R^{\pm}$, all leptogenesis models may be classified into two groups:

- A lepton asymmetry is generated at a very high scale either in the context of D-parity breaking LRSM or through some other interactions, both thermal and non-thermal.

- A lepton asymmetry is generated at the TeV scale with resonant enhancement, when the left-right symmetry breaking phase transition is taking place.

These discussions are valid for the LRSM with both triplet as well as doublet Higgs scalars. We use the reference of the two variants of the LRSM mentioned above to study the lepton number violating washout processes and demonstrate that all these possible scenarios of leptogenesis are falsifiable for a TeV scale W_R. In models with high-scale leptogenesis with $T > 10^9$ GeV, the low energy $B - L$ breaking is associated with giving mass to the $W_R^{\pm}$, which allows gauge interactions that wash out all the baryon asymmetry before the electroweak phase transition is over. On the other hand, the same lepton number violating gauge interactions will slow down the generation of the lepton asymmetry for resonant leptogenesis at the TeV scale, so that generation of the required baryon asymmetry of the universe is not possible for TeV scale $W_R^{\pm}$.

The most stringent constraints on the $W_R^{\pm}$ mass for successful high-scale leptogenesis for a hierarchical neutrino mass spectrum $(M_{N_{3R}} \gg M_{N_{2R}} \gg M_{N_{1R}} = m_{N_R})$

come from the $SU(2)_R$ interactions [9]. To have successful leptogenesis in the case $M_{N_R} > M_{W_R}$ the out-of-equilibrium condition for the scattering process $e_R^- + W_R^+ \to N_R \to e_R^+ + W_R^-$ gives

$$M_{N_R} \gtrsim 10^{16} \text{ GeV} \quad (5)$$

with $m_{W_R}/m_{N_R} \gtrsim 0.1$. Now for the case $M_{W_R} > M_{N_R}$ leptogenesis can happen either at $T \simeq M_{N_R}$ or at $T > M_{W_R}$ but at less than the $B - L$ breaking scale. Considering the out-of equilibrium condition for the scattering process $e_R^{\pm} e_R^{\pm} \to W_R^{\pm} W_R^{\pm}$ through N_R exchange one obtains the constraint

$$M_{W_R} \gtrsim 3 \times 10^6 \text{ GeV} (M_{N_R}/10^2 \text{ GeV})^{2/3}. \quad (6)$$

Thus observing a W_R signal with a mass in the TeV range for hierarchical neutrino masses rules out the high-scale leptogenesis scenario. In Refs. [10], the constraints obtained from the observation of lepton number violating processes and neutrinoless double beta decay were studied to rule out typical scenarios of high-scale thermal leptogenesis, particularly leptogenesis models with right-handed neutrinos with mass greater than the mass scale observed at the LHC by the CMS experiment. The possibility of generating the required lepton asymmetry with a considerably low value of the W_R mass has been discussed in the context of the resonant leptogenesis scenario [11]. In the LRSM, it has been pointed out that successful low-scale leptogenesis with a quasi-degenerate right-handed neutrinos mass spectrum, requires an absolute lower bound of 18 TeV on the W_R mass [12]. Recently, it was reported that just the right amount of lepton asymmetry can be produced even for a substantially lower value of the W_R mass ($M_{W_R} > 3$ TeV) [13] by considering relatively large Yukawa couplings, which has been updated to 13.1 TeV after a more careful analysis in Ref. [14]. In Refs. [12, 13], the lepton number violating gauge scattering processes such as $N_R e_R \to \bar{u}_R d_R$, $N_R \bar{u}_R \to e_R d_R$, $N_R d_R \to e_R u_R$ and $N_R N_R \to e_R \bar{e}_R$ have been analyzed in detail. However, lepton number violating scattering processes with external W_R have been ignored on the account of the fact that for a heavy W_R, there will be a relative suppression of $e^{-m_{W_R}/m_{N_R}}$ in comparison to the processes with no external W_R. Now if the W_R mass is a few TeV's as suggested by the excess signal at the LHC reported by the CMS experiment then one has to take the latter processes seriously.

In Ref. [15], we had first pointed out that the lepton number violating washout processes ($e_R^{\pm} e_R^{\pm} \to W_R^{\pm} W_R^{\pm}$ and $e_R^{\pm} W_R^{\mp} \to e_R^{\mp} W_R^{\pm}$) can be mediated by doubly charged Higgs scalars in the conventional LRSM. Following that, in Ref. [14] only this channel was considered, and for a particular class of type-I seesaw model with relatively small M_{N_R} it was found to have a small contribution, as expected for a large M_{W_R}/M_{N_R}. However the other gauge scattering processes in that scenario are strong enough to give a lower bound of 13.1 TeV on the W_R mass. In this Letter, we explore the above lepton

number violating scattering processes mediated by both Δ_R^{++} and N_R in a much more general context, where we have also taken into account the interference of these channels. The former channel has one gauge vertex and one Yukawa vertex, while for the latter channel both the vertices are gauge vertices, thus are highly unsuppressed compared to the processes involving Yukawa vertices. We find that the lepton number violating scattering process $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ mediated via both N_R and Δ_R^{++} can stay in equilibrium till the electroweak phase transition for a TeV scale W_R and wash out the lepton asymmetry [1]. Thus if one incorporates the above washout process in the Boltzmann equation for lepton number asymmetry, the mentioned lower limit on M_{W_R} for successful TeV-scale resonant leptogenesis will further go up. In the later variant of LRSM mentioned above the doubly charged Higgs is not there, however, the lepton number violating scattering processes mediated via N_R are still present and will wash out the lepton asymmetry.

In the LRSM, the charged current interaction involving the right-handed neutrino and the right-handed gauge boson is given by

$$\mathcal{L}_N = \frac{1}{2\sqrt{2}} g_R J_{R\mu} W_R^{-\mu} + h.c. \tag{7}$$

where $J_{R\mu} = \bar{e}_R \gamma_\mu (1 + \gamma_5) N_R$. The Lagrangian for the right-handed Higgs triplet is given by

$$\mathcal{L}_{\Delta_R} \supset \left(D_{R\mu} \vec{\Delta}_R \right)^\dagger \left(D_R^\mu \vec{\Delta}_R \right), \tag{8}$$

where $\vec{\Delta}_R = \left(\Delta_R^{++}, \Delta_R^+, \Delta_R^0 \right)$ in the spherical basis and the covariant derivative is defined as $D_{R\mu} = \partial_\mu - ig_R \left(T_R^j A_{R\mu}^j \right) - ig' B_\mu$. The $A_{R\mu}^j$ and B_μ are gauge fields associated with $SU(2)_R$ and $U(1)_{B-L}$ groups with the gauge couplings given by g_R and g' respectively. After spontaneous breaking of the left-right symmetry by giving VEV to the neutral Higgs field Δ_R^0 i.e. $\langle \Delta_R^0 \rangle = \frac{1}{\sqrt{2}} v_R$, the interaction between the doubly charged Higgs triplet and the gauge boson W_R will be given by [16]

$$\mathcal{L}_{\Delta_R} \supset \left(-\frac{v_R}{\sqrt{2}} \right) g_R^2 W_{\mu R}^- W_R^{-\mu} \Delta_R^{++} + h.c. \tag{9}$$

The Yukawa interaction between the lepton doublet $\psi_{eR} = (N_R, e_R)^T$ and the Higgs triplet $\vec{\Delta}_R$ will be given by

$$\mathcal{L}_Y = h_{ee}^R \overline{(\psi_{eR})^c} \left(i\tau_2 \vec{\tau} \cdot \vec{\Delta}_R \right) \psi_{eR} + h.c., \tag{10}$$

where τ's are the Pauli matrices. By giving a VEV to the neutral Higgs triplet field, the Yukawa coupling can

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[1] Note that the other scattering process is doubly phase space suppressed at a temperature below the W_R mass and hence we will not consider it for leptogenesis at $T \lesssim M_{W_R}$.

be expressed as $h_{ee}^R = \frac{M_{N_R}}{2v_R}$ where M_{N_R} corresponds to mass of the Majorana neutrino (N_R).

The Feynman diagrams of the lepton number violating scattering process induced by the above interactions are shown in Fig. 1. Utilizing the interactions in Eqs.
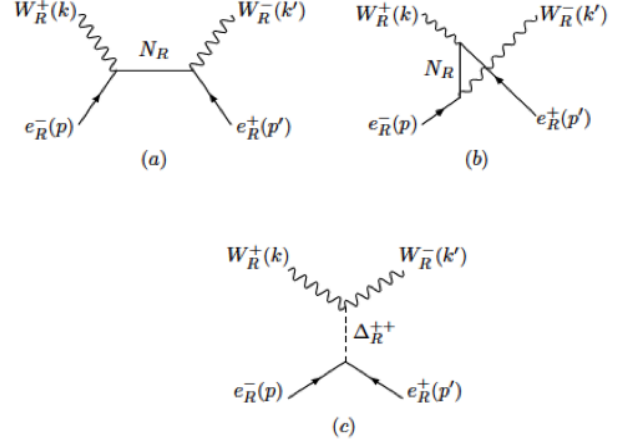

FIG. 1: Feynman diagrams for $e_R^- W_R^+ \to e_R^+ W_R^-$ scattering mediated by N_R and Δ_R^{++} fields. The Feynman diagrams for $e_R^- e_R^- \to W_R^- W_R^-$ are the same as above with appropriate change in direction of the external lines.

(7)-(10), the differential scattering cross section for the $e_R^\mp(p) W_R^\pm(k) \to e_R^\pm(p') W_R^\mp(k')$ process is given by [16]

$$\frac{d\sigma_{e_R W_R}^{e_R W_R}}{dt} = \frac{1}{384\pi M_{W_R}^4 \left(s - M_{W_R}^2 \right)^2} \Lambda_{e_R W_R}^{e_R W_R}(s, t, u), \tag{11}$$

where

$$\Lambda_{e_R W_R}^{e_R W_R}(s, t, u) = \Lambda_{e_R W_R}^{e_R W_R}(s, t, u) \Big|_{N_R} + \Lambda_{e_R W_R}^{e_R W_R}(s, t, u) \Big|_{\Delta_R^{++}} \tag{12}$$

and

$$\Lambda_{e_R W_R}^{e_R W_R}(s, t, u) \Big|_{N_R} = g_R^4 \left\{ -t \left| M_{N_R} \left(\frac{s}{s - M_{N_R}^2} + \frac{u}{u - M_{N_R}^2} \right) \right|^2 \right.$$
$$- 4 M_{W_R}^2 \left(su - M_{W_R}^4 \right) (s-u)^2 \left| \frac{M_{N_R}}{\left(s - M_{N_R}^2 \right) \left(u - M_{N_R}^2 \right)} \right|^2$$
$$\left. - 4 M_{W_R}^4 t \left(\left| \frac{m_{N_R}}{\left(s - M_{N_R}^2 \right)} \right|^2 + \left| \frac{M_{N_R}}{\left(u - M_{N_R}^2 \right)} \right|^2 \right) \right\}, \tag{13}$$

$$\Lambda_{e_R W_R}^{e_R W_R}(s, t, u) \Big|_{\Delta_R^{++}} = 4 g_R^4 (-t) \left\{ \frac{(s+u)^2 + 8 M_{W_R}^4}{\left(t - M_{\Delta_R}^2 \right)^2} |M_{N_R}|^2 \right.$$
$$+ \frac{(s+u)}{t - M_{\Delta_R}^2} |M_{N_R}|^2 \left(\frac{s}{s - M_{N_R}^2} + \frac{u}{u - M_{N_R}^2} \right)$$
$$\left. + \frac{4 M_{W_R}^4}{t - M_{\Delta_R}^2} |M_{N_R}|^2 \left(\frac{1}{s - M_{N_R}^2} + \frac{1}{u - M_{N_R}^2} \right) \right\}, \tag{14}$$

where we have neglected any mixing between W_L and W_R. Note that on the r.h.s. of Eq. (14) the first term represents the Higgs scalar exchange itself while the last two terms correspond to the interference between the Higgs scalar exchange and the N_R exchange mechanisms. The relation between Mandelstem variables $s = (p+k)^2$, $t = (p-p')^2$ and $u = (p-k')^2$ and scattering angle θ is given by

$$\begin{pmatrix} st \\ su - M_{W_R}^4 \end{pmatrix} = -\frac{1}{2}\left(s - M_{W_R}^2\right)^2 (1 \mp \cos\theta). \quad (15)$$

The differential scattering cross section for the $e_R^\pm(p)e_R^\pm(p') \to W_R^\pm(k)W_R^\pm(k')$ process is given by [16]

$$\frac{d\sigma_{W_R W_R}^{e_R e_R}}{dt} = \frac{1}{512\pi M_{W_R}^4 s^2}\Lambda_{W_R W_R}^{e_R e_R}(s,t,u), \quad (16)$$

where

$$\Lambda_{W_R W_R}^{e_R e_R}(s,t,u) = \Lambda_{W_R W_R}^{e_R e_R}(s,t,u)\big|_{N_R} + \Lambda_{W_R W_R}^{e_R e_R}(s,t,u)\big|_{\Delta_R^{++}}. \quad (17)$$

The expressions of $\Lambda_{W_R W_R}^{e_R e_R}(s,t,u)$ in this case are obtained by interchanging $s \leftrightarrow t$ in $\Lambda_{e_R W_R}^{e_R W_R}(s,t,u)$: $\Lambda_{W_R W_R}^{e_R e_R}(t,s,u) = -\Lambda_{e_R W_R}^{e_R W_R}(s,t,u)$. In this case, the Mandelstem variables $t = (p-k)^2$ and $u = (p-k')^2$ are related to $s = (p+p')^2$ and scattering angle θ by

$$\begin{pmatrix} t \\ u \end{pmatrix} = -\frac{s}{2}\left(1 - \frac{2M_{W_R}^2}{s}\right)\left\{1 \mp \sqrt{1 - \left(\frac{2M_{W_R}^2}{s - 2M_{W_R}^2}\right)^2}\cos\theta\right\}. \quad (18)$$

During the period $v_R > T > M_{W_R}$, both the lepton number violating processes are very fast without any suppression. To get an idea of the effectiveness of these scattering processes in wiping out the lepton asymmetry, we estimate the parameter

$$K \equiv \frac{n\langle\sigma|v|\rangle}{H}, \quad (19)$$

for both the processes, where n is the number density of relativistic species and is given by $n = 2 \times \frac{3\zeta(3)}{4\pi^2}T^3$, H is the Hubble rate given by $H \simeq 1.7 g_*^{1/2}T^2/M_{\text{Pl}}$, where $g_* \sim 100$ corresponds to the number of relativistic degrees of freedom, and $\langle\sigma|v|\rangle$ is the thermally averaged cross section. In order to obtain a rough estimate of v_R, let us draw an analogy with the Standard Model, where we have $\langle\phi\rangle = \frac{v_L}{\sqrt{2}}$ where $v_L = 246\,\text{GeV}$, and $M_{W_L} \sim 80\,\text{GeV}$. Now in the LRSM scenario, where we have $\langle\Delta_R^0\rangle = \frac{v_R}{\sqrt{2}}$ breaking the left-right symmetry and $M_{W_R} = g_R v_R$. Then taking $g_R \sim g_L$, we have $\frac{\langle\phi\rangle}{M_{W_L}} = \frac{\langle\Delta_R^0\rangle}{M_{W_R}} \approx 3$.

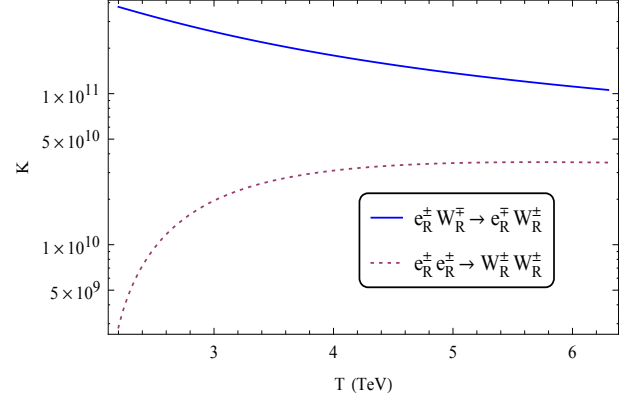Using the differential cross-section given in Eqs. (11) and (16), we plot the behavior of K as a function

FIG. 2: Plot showing K as a function of temperature (T) with $M_{W_R} = 2.1\,\text{TeV}$ for the scattering processes $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ and $e_R^\pm e_R^\pm \to W_R^\pm W_R^\pm$ (including both Δ_R^{++} and N_R mediated diagrams) for $v_R > T > M_{W_R}$.

of temperature in the range $3M_{W_R} > T > M_{W_R}$ for $M_{W_R} = 2.1\,\text{TeV}$ (in the mass range of CMS excess) in Fig. 2. The high value of K in Fig. 2 for both the processes implies that these scattering processes are very fast in washing out lepton asymmetry for $T \gtrsim M_{W_R}$. In the variant of LRSM with doublet Higgs scalars the scattering processes cannot be mediated via a doubly charged Higgs scalar. However, these lepton number violating scattering processes can still be mediated via heavy neutrinos, which washes out the lepton asymmetry in this scenario for $T \gtrsim M_{W_R}$.

For $T < M_{W_R}$, the process $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ is more important [1]. Below we will estimate a lower bound on T till which the latter process stays in equilibrium below $T = M_{W_R}$. The cross section of this process as a function of temperature T can be obtained from Eq. (11). The scattering rate is given by [2] $\Gamma = \bar{n}\langle\sigma v_{\text{rel}}\rangle$. At a temperature $T < M_{W_R}$ the number density $\bar{n} = g\left(\frac{TM_{W_R}}{2\pi}\right)^{3/2}\exp\left(-\frac{M_{W_R}}{T}\right)$ accounts for the Boltzmann suppression of the scattering rate. The condition for the scattering process to be in thermal equilibrium is $\Gamma > H$. Using $M_{N_R} \lesssim M_{W_R}$ and $v_{\text{rel}} = 1$ we plot the temperature till which the scattering process $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ stays in equilibrium as a function of the M_{W_R} in Fig. 3 for three different values of M_{Δ_R}. We have chosen the lowest value of M_{Δ_R} to be $500\,\text{GeV}$ in accordance with the recent search limits on the doubly charged Higgs boson mass [17]. The plot clearly shows that unless M_{W_R} is significantly larger than the TeV scale, the scattering process $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ will stay in equilibrium till a temperature close to the electroweak phase transition and

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[2] We have ignored any finite temperature effects to simplify the analysis. These effects are small and do not change our conclusions.
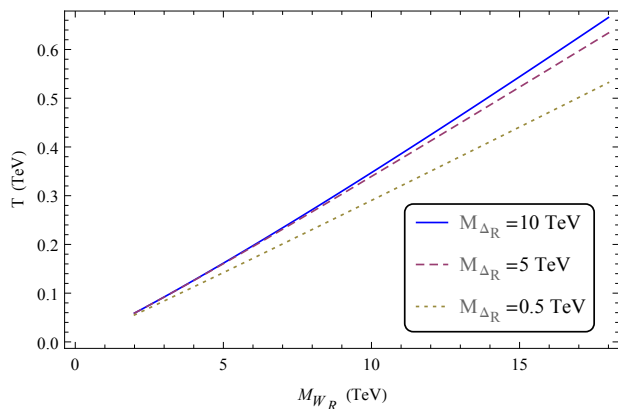
FIG. 3: Plots showing the out-of-equilibrium temperature (T) of the scattering process $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$ (mediated via Δ_R^{++} and N_R fields) as a function of M_{W_R} for three different values of M_{Δ_R} and $M_{N_R} \sim M_{W_R}$.

will continue to wash out the lepton asymmetry till that temperature. In the LRSM scenario with doublet Higgs scalars, the lepton number violating scattering processes mediated only via heavy neutrinos will continue to wash out the asymmetry till the electroweak phase transition, pushing up the lower limit on the W_R mass for a successful leptogenesis scenario far beyond the W_R signal range reported by the CMS experiment, ruling out the possibility of generating the observed baryon asymmetry from TeV scale resonant leptogenesis as well.

To conclude, for the high-scale leptogenesis scenario ($T \gtrsim M_{W_R}$), in both the variants of the LRSM the lepton number violating scattering processes ($e_R^\pm e_R^\pm \to W_R^\pm W_R^\pm$ and $e_R^\pm W_R^\mp \to e_R^\mp W_R^\pm$) are very efficient in wiping out the lepton asymmetry, while for a TeV scale resonant lepto-

genesis scenario the latter process will stay in equilibrium till the electroweak phase transition, washing out the lepton asymmetry for $T < M_{W_R}$. Hence we rule out the possibility of successful leptogenesis for $W_R^\pm$ with mass in the TeV range

- in all possible high-scale leptogenesis scenarios for the LRSM variants with (i) triplet Higgs and (ii) doublet Higgs, and

- in TeV scale resonant leptogenesis scenarios for LRSM variants with (i) triplet Higgs and (ii) doublet Higgs.

Complementing the above results, we have also explored the low-energy subgroups of superstring motivated E_6 model in recent works. In one of the supersymmetric low-energy subgroups of the E_6 (known as the Alternative Left-Right Symmetric Model) one can allow for high-scale leptogenesis, and explain the excess signal at the LHC reported by the CMS experiment from resonant slepton decay. However, the excess signal cannot be explained by right-handed gauge boson decay while allowing leptogenesis, in both supersymmetric and non-supersymmetric low-energy subgroups of superstring motivated E_6 model [18]. Thus, in light of the above, if the two leptons and two jets excess at the LHC reported by the CMS experiment is indeed due to $W_R^\pm$ decay, then one needs to resort to a post-electroweak phase transition mechanism to explain the baryon asymmetry of the Universe and in this context, the experiments to observe the neutron-antineutron oscillation [19] or $(B - L)$ violating proton decay [20] will play a crucial role in confirming such possibilities.

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